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INSTREAM FLOW NEEDS BIOLOGICAL LITERATURE REVIEW

SUSQUEHANNA RIVER BASIN COMMISSION

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The Susquehanna River Basin Commission was created as an independent agency by a federal-interstate compact* among the states of Maryland, New York, Commonwealth of Pennsylvania and the federal government. In creating the Commission, the Congress and state legislatures formally recognized the water resources of the Susquehanna River Basin as a regional asset vested with local, state and national interests for which all the parties share responsibility. As the single federal-interstate water resources agency with basinwide authority, the Commission's goal is to effect coordinated planning, conservation, management, utilization, development and control of basin water resources among the government and private sectors.

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INSTREAM FLOW NEEDS

BIOLOGICAL LITERATURE REVIEW

Prepared by:

David W. Heicher
Program Specialist

SUSQUEHANNA RIVER BASIN COMMISSION
1721 North Front Street
Harrisburg, PA 17102

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PREFACE

This report was prepared to aid the Instream Flow Subcommittee (IFS) of the SRBC's Water Resourcesw Management Advisory Committee (WRMAC) in addressing biological instream flow needs in the Susquehanna River basin. The IFS was created as an interagency, interdisciplinary technical advisory body to provide specific advice on the scope of work and methodology to be used in a comprehensive study to define the instream flow needs in the Susquehanna River Basin. The IFS was also directed to serve as a technical advisory committee during the course of the instream flow study and to assist in interpreting the study results. The IFS has also been requested to provide advice on the merits of the Commission's consumptive use makeup regulation (18 CFR Section 803.61) and the appropriateness of the Q7-10 flow as the trigger flow in that regulation.

This report was presented and discussed at the initial meeting of the IFS which was held on October 28, 1992. Editorial comments were received from the IFS members and appropriate revisions have been made to the original text.

INTRODUCTION

Flowing water is a key component of lotic environments (Odum, 1956; Hynes, 1970a). Adequate streamflow is required for the maintenance of fish and wildlife populations, for primary production by algae and aquatic plants, for the conversion of plant to animal matter by benthic macroinvertebrates, and for the maintenance of other components of aquatic food webs. Adjacent wetlands and riparian vegetation may also be dependent on adequate streamflow.

The purpose of this report is to review the biological effects associated with low flows and to examine and compare methods that have been developed to identify biological instream flow needs. Areas for further investigation are identified and discussed.

Potential impacts to recreation, aesthetics, hydropower, navigation, and other components of the human environment may also be important in identifying instream flow needs for specific water bodies. Information concerning recreational instream flow requirements is contained in publications by Andrews and Madsen (1976), Andrews _et al_. (1976), Chubb and Bauman (1977), Hyra (1978), Daubert and Young (1981), and Brown _et al_. (1991). Discussions regarding aesthetic instream flow needs are contained in publications by Andrews and Madsen (1976) and Masteller _et al_. (1976). Economic considerations are presented by Loomis (1987), Saliba (1987), Ward (1987), Johnson and Adams (1988), and Loomis and Cooper (1990).

Decreases in streamflow may be caused by drought, out-of-stream diversions, and reservoir operation schemes. The presence and operation of a reservoir can cause impacts in addition to those caused by low flows. Reservoirs change lotic to lentic habitat and can block fish migration, alter downstream channel morphology, block the natural transport of sediments and food materials, and alter downstream water quality. Reservoirs can be operated to rapidly increase or decrease the flow of water below the dam. They can also be used to periodically augment natural streamflow. Information regarding the effects of reservoir operation is contained in publications by Spence and Hynes (1971a), Spence and Hynes (1971b), Oglesby _et_ _al_. (1972), Hagan and Roberts (1973), Ward and Stanford (1979), Brooker (1981), Lillehammer and Saltveit (1984), and Bulak and Jobsis (1989).

Reservoir management plans play a key role in determining the balance between beneficial and adverse effects. However, a detailed analysis of the impact of reservoirs and their management is beyond the scope of this report.

GENERAL CONSIDERATIONS REGARDING SEDIMENTATION, STREAM MORPHOLOGY, AND WATER QUALITY

When the natural flow of streams is altered by water resource development projects, the magnitude and duration of peak flows are generally reduced. Flow reduction makes less energy available for sediment transport and can lead to the accumulation of fine sediments on the stream bottom (Rosegen et al., 1986). Sedimentation effects may be especially noticeable immediately downstream of tributaries that carry high sediment loads (Brooker, 1981).

Alteration of the range and duration of flows can change the morphology of the stream channel and floodplain (Rosegen et al., 1986; Bleed, 1987). In some streams with reduced flow, the channel may become choked with vegetation, which may further alter streamflow and channel morphology (Stanford and Ward, 1979; Bleed, 1987; Sherrard and Erskine, 1991). Because stream channels do not always respond to incremental changes in a gradual fashion, a small change in flow may sometimes produce a large effect on channel morphology (Bleed, 1987).

Lanka et al. (1987) demonstrated that drainage basin geomorphology in small, Rocky Mountain streams can influence aquatic habitat and trout standing stock. Hill et al. (1991) stated that fluvial-geomorphic processes form and control fish habitat. Long-term changes in stream morphology have the potential to produce significant changes in the distribution and abundance of stream biota.

Reduced flow can aggravate the effects of pollutant loadings by reducing the dilution capacity of the waterway. Winds, bank storage, spring seepage, tributary streams, and the warming effect of the sun usually have a greater effect on stream water temperatures during low flow periods (Fraser, 1972). Low flows in winter can contribute to lowered water temperatures and can sometimes encourage the formation of anchor ice.

Increases in temperature cause a reduction in the amount of dissolved oxygen that can limit the growth, reproduction, and survival of most aquatic life (Hynes, 1970a; Filipek _et_ _al_., 1987). The combined effects of increased temperature and reduced oxygen content are often most critical during summer low flow periods.

Riffles and other irregularities in the stream channel cause water turbulence that assists in replenishing dissolved oxygen. Turbulence is generally reduced during low flow periods.

Maintenance of substrate quality, channel morphology, and water quality are essential for the continued existence of individual stream systems. Setting instream goals based solely on short term flow requirements for aquatic life may be shortsighted if the morphological integrity of the stream is ignored (Rosegen _et_ _al_., 1986; Bleed, 1987; Hill _et_ _al_., 1991).

Hill _et_ _al_. (1991) stated that managing streamflows solely on the basis of perceived fishery needs may result in stream channel degradation, alteration of geomorphological processes, changes in riparian vegetation, and alteration of floodplain function. They suggested a holistic approach that would consider (1) flood flows that influence the formation of floodplain and valley features, (2) overbank flows that help maintain wetland

and riparian habitat, (3) flows for the maintenance of channel morphology, and (4) flows for aquatic habitat. In a case study of an Idaho stream, they demonstrated how multiple flow analyses could be performed with methods that are currently available.

A detailed analysis of methodologies for predicting impacts to substrate quality, stream morphology and water quality is beyond the scope of this report. However, appropriate consideration should be given to the maintenance of these habitat components to insure the validity of biological instream flow studies.

EFFECTS OF LOW FLOWS ON AQUATIC AND RIPARIAN BIOTA

Wetland and Riparian Vegetation

Most obligate wetland plant species have physiological adaptations for life in saturated or moist soil conditions. Some wetlands require periodic inundation to maintain their productivity (Kadlec, 1976b; Cowardin et al., 1979, Stanford and Ward, 1979). Other riparian vegetation may also benefit from moisture and nutrients provided by periodic flooding. Lowering the water table or reducing overbank flooding may result in changes in the density, productivity, and species composition of wetland and riparian vegetation (Kondolf et al., 1987).

Vegetation can affect the morphology and flow characteristics of stream channels. Conversely, streamflow can affect riparian and wetland vegetation (Bleed, 1987; Kondolf et al.,1987; Nilsson, 1984; Stromberg and Patten, 1990; Stromberg and Patten, 1991; Sherrard and Erskine, 1991).

Woody vegetation provides protection from channel erosion and provides cover and habitat diversity (Beschta and Platts, 1986). In some instances, an individual tree may influence the characteristics of a small stream channel for many decades.

Riparian vegetation provides shade and helps to moderate daily fluctions in stream temperature. Vegetation also provides allochthonous plant material consisting of dead and decaying detritus, which serves as an important energy source for lotic systems (Hynes, 1970b; Vannote et al., 1980). Terrestrial insects falling from streamside vegetation may serve as a source of food for aquatic life during certain times of the year.

Riparian and wetland vegetation help regulate biogeochemical cycles, influence water quality, affect the duration and magnitude of flooding, and provide food, water, cover, nesting sites, and migration corridors for a wide variety of game and non-game wildlife species (Kondolf _et al_., 1987). Changes in the abundance and species composition of riparian vegetation may alter the width and depth of stream channels, increase stream temperatures in summer and decrease them in winter, and decrease the supply of fishfood organisms (Beschta and Platts, 1986).

Periphyton, Submerged Vascular Plants, and Benthic Macroinvertebrates

Streamside vegetation plays a major role in determining the balance between autotrophy and heterotrophy in small streams (Cummins, 1979). The degree to which the stream is autotrophic or heterotrophic is primarily dependent on shading (Minshall, 1978). A continuous gradient of physical conditions is responsible for the continuum of species found between the headwaters of a stream and its mouth (Vannote _et al_., 1980). In larger streams, the importance of food supplies from terrestrial origins decreases, while autochthonous primary production and downstream transport of organic materials become more important.

Primary production by periphyton and submerged plants is generally of most importance in medium-sized rivers (Vannote _et al_., 1980). In larger rivers, light may be limited by water depth and turbidity.

Cummins (1979) stated that even under limited light conditions, periphyton may be more abundant if flood flows are not available to scour the stream substrate. He reported that during the 1977 drought in the northwestern United States, unusually high standing crops of attached algae occurred in headwater streams during the fall and winter, which are normally periods of increased streamflow. Increases in periphyton as well as changes in aquatic vascular plant populations have been reported in regulated streams having decreased flushing flows (Lowe, 1979; Stanford and Ward, 1979; Armitage, 1984; Skulberg, 1984). Although more constant flow can contribute to increased production by algae and aquatic plants, the reverse may be true if increased sedimentation also occurs (Ward, 1976). Flushing flows which release detritus and displace periphyton are important reset mechanisms that are needed for the continued integrity of stream ecosystems (Cummins, 1979).

Decreases in streamflow that cause changes in the relative abundance of algae, allochthonous material, and organics can strongly influence the abundance and distribution of benthic macroinvertebrates (Cummins, 1979; Vannote, 1980). Williams and Winget (1979) observed an increase in aquatic macrophytes, algae, and the benthic algal scrapers Baetis sp. and Micrasema sp. in response to decreased flows in the Strawberry River, Utah. Other changes that they observed included an increase in filter feeding simuliidae and increased numbers of low flow tolerant organisms such as Paraleptophlebia sp., chironomids, and oligochaetes. Populations of elmid beetles and the detrital feeders/shredders Ephemerella grandis, Pteronarcella badia, and Hexatoma sp. were reduced or eliminated.

Reduced flows can decrease the wetted surface area available as benthic habitat. Elevated water temperatures and reduced oxygen content that are frequently associated with low flows can also cause adverse effects on benthic macroinvertebrates. Siltation can alter the stream bottom and can cause the clogging of interstitial spaces between larger stream sediments (Ward, 1976; Armitage, 1984; Beschta and Platts, 1986). The quality of stream substrate has a profound influence on the ecology of benthic macroinvertebrate communities (Hynes, 1970a; Cummins, 1974; Ward, 1976) since many benthic species are adapted to life on or in specific substrate types.

The hyporheic zone beneath the surface of the stream bed provides habitat for many species of benthic macroinvertebrates (Coleman and Hynes, 1970) and may serve as a refuge from drought, floods, anchor ice, and high temperatures (Ward, 1976). Degradation of the hyporheic zone by siltation would be expected to have an adverse effect on benthic macroinvertebrate populations.

Many lotic benthic species have behavioral or physiological adaptations that make them dependent on a specific range of current velocity for their survival (Hynes, 1970a; Ward, 1976). Reduced flow generally decreases the number of current microhabitats available for colonization and limits species diversity.

Invertebrate drift is a natural occurrence that is valuable in redistributing benthic species to downstream areas. Although increased drift can occur due to flushing action during high flow events, reductions in discharge can also cause increased invertebrate drift (Radford and Hartland-Rowe, 1971; White _et al._, 1981), especially when the reduction in current velocity is large (Minshall and Winger, 1968). Water management practices that cause frequent reductions in stream velocity have the potential to move large numbers of benthic macroinvertebrates due to invertebrate drift.

Fish

Reduced streamflow affects the quantity and quality of aquatic habitat. Although extreme low flow events produce obvious and immediate decreases in fish populations, more subtle reductions in flow occurring over an extended time period tend to be equally, if not more important to the long term stability of the fishery.

When normal streamflow is restored after severe low flow conditions, different species are able to recolonize the stream at different rates (Larimore, _et al._, 1959; Hynes, 1970b). An increased frequency of low flow events on a particular stream will tend to create a population shift in favor of the more resilient species.

Generally, decreases in fish habitat do not occur in direct proportion to decreases in flow. The effect on usable habitat is a function of stream morphology and the habitat requirements of the species involved (Fraser, 1972). Habitat that is chronically affected by reduced flow can give competitive advantages to some species at the expense of others, resulting in long-term changes in species distribution and abundance.

Water velocity and depth are among the most important physical parameters influencing fish (Hynes, 1970a; Stalnaker, 1979; Newcombe, 1981; Orth and Maughan, 1982; Bulak and Jobsis; 1989). Many species are adapted to a limited range of current velocities or water depths, which are affected by reduced flow (Fraser, 1972).

Reduced current velocity can produce behavioral changes in some fish species (Campbell _et_ _al_., 1984) and can influence relationships between food and space requirements (Chapman, 1966; Lewis, 1969; Fraser, 1972). Territorial behavior can be influenced by current velocity (Fraser, 1972). Reduced velocities can cause individual fish to increase the size of their defended territories, thereby displacing smaller and less agressive fish. The more agressive fish control larger areas of stream habitat and less room is available for use by others. The increased territorial behavior during low flow events can decrease the carrying capacity of the stream due to increased competition (Fraser, 1972).

Very low flows can cause mortality due to stranding and can increase vulnerability to predators (Fraser, 1972; Kroyer, 1973). Crowding in the remaining available habitat can increase stress and decrease resistance to disease and parasites (Filipek _et_ _al_., 1987; Peters, 1982). Reduced flows can also make fish more vulnerable to angling pressure (Fraser, 1972).

Many researchers have documented the importance of adequate flow for the spawning and reproductive success of salmonids and other coldwater species. Flow can be equally important to warmwater species that spawn in the slower sections of streams or in areas that are seasonally flooded (Fraser, 1972). Many species depend on annual flooding to provide food and spawning sites.

Inadequate flow can cause some species to delay migration and can create physical barriers to upstream and downstream movement (Fraser, 1972; Bulak and Jobsis, 1989). Reduced flow after spawning can leave fish eggs stranded out of water, decrease current velocity needed for successful hatching, and crowd nursery habitat (Peters, 1982).

Siltation and water quality effects associated with chronic low flows can alter the distribution and abundance of both fish and fishfood organisms. Temperature changes have the potential to affect fish spawning, growth, and metabolism (Hynes, 1970a). Tolerances to increased temperature and lowered dissolved oxygen concentrations vary greatly with individual fish species (Hynes, 1970a; Filipek *et al*., 1987).

Wildlife

Few publications address the effects of low flows on wildlife. Kadlec (1976a, 1976b) listed four effects that may be associated with reduced flow: (1) removal of drinking water; (2) reduction of habitat for aquatic species such as beaver, muskrat, and waterfowl; (3) alteration of riparian vegetation; and (4) changed flooding patterns affecting wetland habitat. Of the above, he suggested that changes in riparian vegetation and wetland habitat may have the greatest potential to permanently affect wildlife populations.

METHODS FOR DETERMINING INSTREAM FLOW NEEDS

Wetland and Riparian Vegetation

Although the dependence of riparian vegetation on streamflow is generally accepted, few methods have been developed to determine the instream flow needs of riparian vegetation (Kondolf *et al*., 1987; Stromberg and Patten, 1990). A promising area for future research is the relationship between tree ring growth and historic streamflow records.

Stromberg and Patten (1990) analyzed riparian tree ring growth and historic flow records for Rush Creek, California and determined that flow volume is important to riparian growth in that watershed. They postulated that since many instream flow methods focus on aquatic life, there is a potential to underestimate the needs of the entire riparian system. By comparing the size of tree ring growth with historic flow records, it should be possible to establish whether similar relationships exist at other sites.

The impact of flow on wetland and riparian vegetation may be greatest in arid regions and in areas where streamflow is lost to ground water (Bleed, 1987; Stromberg and Patten, 1990). Losing stream reaches may be found in areas that have alluvial sediments or are underlain by carbonate rock. Kondolf *et al*. (1987) suggest that identifying the geomorphic setting, the nature of interactions between streamflow and the water table, and whether individual stream reaches are gaining or losing flow to ground water will assist in determining whether wetland and riparian vegetation may be affected. A general knowledge of the water requirements of the individual plant species and communities that may be affected would assist in this determination.

Periphyton, Submerged Vascular Plants, and Benthic Macroinvertebrates

Few methods exist for evaluating the effects of low flows on periphyton, submerged vascular plants, and benthic macroinvertebrates. In general, many of the fishery evaluation methods discussed later in this report assume that if habitat requirements for fish are met, other aquatic life will also survive.

Due to the limited mobility of benthic macroinvertebrates, Gore and Judy (1981) reasoned that these organisms may be more sensitive to flow alterations than fish. They stated that a streamflow management strategy should identify flows needed to maintain benthic macroinvertebrates, which are often the primary source of food for fish.

Gore (1978) discussed a method that uses information regarding benthic macroinvertebrate density and physical microhabitat features to identify minimum flow requirements. After the Instream Flow Incremental Methodology (IFIM) was developed (see discussion of fishery methods below), Gore and Judy (1981) proposed a similar method for determining streamflow requirements for benthic macroinvertebrates. This method may be of particular value when an endangered or threatened species or an important food organism may be affected by reduced flow.

Fish

Many researchers have attempted to develop a simple, cost effective, and accurate means of identifying instream flow requirements for fishery resources. In 1987, Filipek *et al.* reported that nearly 40 methods had been developed. Although research efforts have been intense, no single method has been developed that is ideal for all applications.

Reviews and comparisons of existing instream flow evaluation methods for fishery resources are contained in publications by Bayha (1978), Wesche and Rechard (1980), Loar and Sale (1981), Orth and Maughan (1982), Annear and Conder (1984), Estes and Orsborn (1986), Leonard *et al.* (1986), Barrett and Jakle (1987), Filipek (1987), Bulak and Jobsis (1989), Reiser *et al.* (1989), and Orth and Leonard (1990). Methods in use range from simple, office-based procedures such as the Tennant Method (Tennant, 1975, 1976a, 1976b) to complex procedures such as the IFIM (Bovee, 1982). Descriptions of the more frequently used methodologies are presented below.

Q7-10 Value. The 7-day 10-year low flow (Q7-10) value is sometimes used as a minimum instream flow requirement. The Q7-10 value is defined as the minimum low flow for a period of seven consecutive days that occurs on the average once every 10 years. The Q7-10 value is used as a design standard for the return flows from wastewater treatment plants. As long as the Q7-10 flow is maintained, the wastewater treatment plant discharge theoretically should not cause a violation of water quality standards in the receiving stream. The Q7-10 value is used most frequently as an instream flow standard in eastern states and is generally applied in streams where water quality problems exist (Reiser et al., 1989).

Bovee (1982) stated that from the standpoint of a fishery biologist, the Q7-10 level would be a ridiculously low level at which to begin streamflow protection. Stalnaker (1981) and Loar and Sale (1981) recommended against using a single low flow criterion in setting instream flow goals since the criterion selected eventually becomes the norm and drought conditions may be maintained in perpetuity. They specifically recommended against using the Q7-10 value, which has little relationship to fishery needs. Bulak and Jobsis (1989) also criticized the use of the Q7-10 value for flow recommendations and stated that Q7-10 flows should not be recommended to protect tailwater fisheries.

Camp Dresser and McKee (1986) recommended against using the Q7-10 flow as a minimum instream flow standard because: 1) the Q7-10 value is sometimes zero, 2) the Q7-10 value is not related to aquatic life protection goals with respect to the volume of flow, and 3) the Q7-10 value does not ensure aquatic life protection since pollutant discharges may continue if streamflow drops below the Q7-10 level. They also noted that the Q7-10 value is typically less than the level that the Tennant Method cites for the short term survival of aquatic life. They stated that since there is no direct relationship between the Q7-10 value and aquatic life protection, multiples of the Q7-10 value are also not directly related to these goals.

Professional Judgment. The professional opinion of a biologist familiar with the stream in question is sometimes used as the basis for identifying instream flow requirements. Some degree of professional judgment is needed to reasonably perform all instream flow evaluation methodologies. Although professional judgment may yield accurate results, the answer is qualitative and will vary depending on the experience and perceptions of the person performing the evaluation (Barrett and Jakle, 1987).

Tennant Method. The Tennant or Montana Method (Tennant, 1975, 1976a, 1976b) was one of the first instream flow methods to be developed specifically for the protection of aquatic life and is still in widespread use today. Reiser et al. (1989) reported that based on their survey of 46 states and 12 Canadian provinces, the Tennant Method was the second most commonly used or recognized method. The method is quick and easy to use and requires little or no field work. It is generally used for routine or reconnaissance level work when the investment of time and money for detailed biological studies is not appropriate.

Tennant (1975, 1976a, 1976b) developed the method by conducting detailed field studies on 11 streams in three states between 1964 and 1974. Studies were conducted in both coldwater and warmwater streams with the help of state fishery biologists. The study results indicated that aquatic habitat conditions were similar on most of the streams that carried the same portion of their average flow. Similar studies of hundreds of streamflow regimens in 21 states were used by Tennant to confirm his findings. Streamflow recommendations for various purposes for the periods October-March and April-September were presented in tabular form as specified percentages of the stream's average daily flow. The information in Table 1 of Tennant's publications summarizes his recommendations for the protection of fish, wildlife, and recreation and is reproduced below.

TABLE 1

Instream Flow Regimens for Fish, Wildlife, Recreation, & Related Environmental Resources

Description of Flows	Recommended Base Flow Regimens	
	Oct.-Mar.	Apr.-Sept.
Flushing or maximum	200% of avg. flow	
Optimum range	60%-100% of avg. flow	
Outstanding	40%	60%
Excellent	30%	50%
Good	20%	40%
Fair or degrading	10%	30%
Poor or minimum	10%	10%
Severe degradation	10% of avg. flow to 0 flow	

In general, the Tennant Method recommends maintenance of 30 percent of the long term average annual flow in order to sustain good conditions for the survival of aquatic life. Ten percent of average annual flow is identified as a minimum flow that is recommended only to provide short-term survival habitat. Tennant recommended against streamflow regimens allowing less than 10 percent of average daily flow since permanent damage to fish and wildlife populations would result. He stated that 60 percent of average annual flow provides excellent to outstanding habitat for most aquatic life during primary growth periods.

The Tennant Method has been tested against other more recent and complex incremental methodologies (Orth and Maughan, 1982; Annear and Conder, 1984; Leonard et al., 1986; Orth and Leonard, 1990) and has generally given satisfactory results. However, the Tennant Method does not quantify the incremental changes in habitat resulting from various levels of flow reduction (Bulak and Jobsis, 1989). The method also is not suited to tradeoff analyses using different hypothetical flow regimes (Annear and Conder, 1984; Bulak and Jobsis, 1989). When the drainage basin for a study stream is large (greater than 750 square miles), the Tennant Method may yield recommended streamflows that are somewhat greater than those recommended by IFIM studies (Leonard, et al., 1986; Camp Dresser and McKee, 1986). Also, the Tennant Method does not account for regional differences in hydrology and stream channel morphology (Leonard et al., 1986).

Modifications of the Tennant Method. A number of modifications of the original Tennant Method have been proposed (Bayha, 1978, Barrett and Jakle, 1987; Filipek, 1987). Although these modifications may improve upon the original method proposed by Tennant, they also do not permit tradeoff analyses of incrementally decreasing flows.

Aquatic Base Flow. The Aquatic Base Flow Method was developed in New England and is primarily used there. The method employs a combination of median flow and constant watershed yield statistics to develop minimum instream flow requirements (Loar and Sale, 1981; Leonard et al., 1986; Kulik, 1990). The Aquatic Base Flow equals the August median monthly flow and is assumed to be an appropriate minimum flow for all times of the year unless additional water is needed for fish spawning and migration. The median monthly flow is only applicable to unregulated streams with good historical streamflow records and a drainage area greater than 50 square miles. For streams that do not meet the above criteria, a constant yield factor is applied to the site to estimate actual flow conditions.

The Aquatic Base Flow Method uses low flow statistics and does not require extensive field investigations. However, it does not relate streamflow to actual biological impacts and is not adapted to permit tradeoff analyses.

Wetted Perimeter. The Wetted Perimeter method is described in publications by Annear and Conder (1984), Leonard et al. (1986), and Barrett and Jakle (1987). In order to use the method, a representative cross section is selected in a riffle in the study area. The wetted perimeter of the stream cross section is then determined by making measurements at various flows or by taking one set of field measurements and calculating the corresponding measurements at simulated flows. Wetted perimeter is then plotted versus discharge on a graph. An inflection point is identified on the graph to determine the recommended instream flow. The inflection point is assumed to identify the flow at which aquatic habitat is lost at an increased rate when streamflow is decreased.

The Wetted Perimeter Method hinges on the assumption that there is a direct relationship between the wetted perimeter and the value of aquatic habitat. This is not always the case. Also, critical cross sections must be selected with care, since conditions may differ at other riffle sites in the study area. Another major drawback of the method is the subjectivity associated with selecting the inflection point (Annear and Conder, 1984; Leonard _et al_., 1986; Barrett and Jakle, 1987). Bulak and Jobsis (1989) note that multiple inflection points or no inflection point may occur when the cross section is irregular or has more than one channel.

R-2 Cross Method. Barrett and Jakle (1987) explained that the R-2 Cross Method was the basis for an entire group of instream flow evaluation techniques including the Single Cross Section, Colorado, Critical Area, and Sag-Tape Methods. They explained that in order to use the basic method, the study area is first divided into segments based on biological, hydrological, or other parameters of concern. Then, transects are established at critical or representative study sites.

Stakes are driven into the ground at the end of each transect and are leveled with each other. A tape is stretched from the top of one stake to the other and measurements from the tape to the ground or stream bottom are taken at intervals along the tape to establish a bottom profile. Current velocities are also measured along the length of the tape. An upstream master reference point is established and the discharge is determined.

A computer program is used to calculate what portions of the stream meet or exceed the specified water depths for a target fish species. The calculations are made for various simulated flows to determine the minimum flow that will support the target species.

The R-2 Cross Method is not used or recognized as widely as the Wetted Perimeter Method (Reiser et al., 1989). Loar and Sale (1981) stated that the R-2 Cross Method is restricted to narrow, wadable streams with uniform or only gradually varied flow.

Instream Flow Incremental Methodology (IFIM). The IFIM is by far the most widely used and recognized instream flow evaluation methodology in the United States and Canada (Reiser et al., 1989). The method was developed in the late 1970's by the Instream Flow Group of the U.S. Fish and Wildlife Service and has been subjected to intense evaluation. In spite of some criticisms (Mathur et al., 1985; Glova and Duncan, 1985; Orth and Maughan, 1986; Conder and Annear, 1987; Pajak and Neves, 1987; Wesche et al., 1987; Gore and Nestler, 1988), the IFIM is generally considered to be the state-of-the-art method available for the evaluation of instream flow requirements for fishery resources (Bulak and Jobsis, 1989).

The IFIM is an interdisciplinary evaluation technique that uses data from site-specific biological and hydrological investigations to compare habitat weighted usable area to discharge. The method involves preparation of habitat suitability curves for selected species and uses a physical habitat simulation (PHABSIM) system, which is a system of computer programs that simulate physical habitat parameters in relation to the flow regime. Various components of species-specific behavioral patterns and open channel hydraulics are simulated and the results are combined to describe how changes in streamflow affect fish habitat. Leonard _et_ _al_. (1986) noted that the three most important system components are the hydraulic programs which constitute the physical component, the species criteria database which is the biological component, and the habitat component which uses the previous two components to calculate the amount of habitat available at various flows.

The general rationale and procedures for use of the IFIM were presented by Stalnaker (1979). A guide for the use of the IFIM has been prepared by Bovee (1982). Bovee and Cochnauer (1977) prepared a detailed paper regarding the development of weighted criteria and Bovee (1986) prepared an additional paper regarding the development and evaluation of habitat suitability criteria. A guide to using the PHABSIM system has been prepared by Milhous _et_ _al_. (1984). The U.S. Fish and Wildlife Service offers training courses on the use of the IFIM.

Wildlife

Although instream flows maintained for fishery resources should usually be adequate to meet wildlife needs (Kadlec,1976a), this may not always be the case. The presence of endangered species, species of special economic, recreational, or ecological importance, or of species dependent on critical riparian or wetland habitat may warrant the need for further investigation.

Kadlec (1976a) suggested that by hypothesizing a series of flow regimes and their effects on habitat type, the effects of habitat alteration could be identified and used for environmental impact assessment. This approach is similar to that used in the Habitat Evaluation Procedures (HEP) developed by the U.S. Fish and Wildlife Service (U.S. Fish and Wildlife Service, 1980a; U.S. Fish and Wildlife Service, 1980b). Habitat suitability index models for use with HEP have been published by the U.S. Fish and Wildlife Service for many aquatic, wetland, and riparian wildlife species.

CONCLUSIONS

Selection of an Instream Flow Evaluation Method

This report has discussed the biological effects of reduced streamflow and has discussed a number of methods for determining biological instream flow needs. The report has purposely not discussed the establishment of instream flow goals which should be formulated after considering both instream flow needs and offstream water uses. Not all needs will be perceived to be of equal importance, so trade-offs will have to occur in order to establish management goals.

Of all the fishery evaluation methods discussed, the IFIM is best adapted for use in tradeoff analyses. The IFIM can be used to provide defensible, site-specific evaluations of the impacts of a wide variety of flow regimes on aquatic habitat. Barrett and Jakle (1987) stated that the IFIM has a strong legal history and that to their knowledge, the IFIM had never been defeated in court.

Although the IFIM is versatile and widely accepted, it is also a very complex method that requires considerable time, money and technical expertise. Barrett and Jakle (1987) noted that the commitment of time does not only include that required for collecting the habitat measurements and manipulating the data, but also includes the time necessary for those using the IFIM to thoroughly understand the method's assumptions, development and limitations.

In light of the above, use of the IFIM should probably be reserved for large or controversial projects. A simpler but tested procedure would be more desirable for most routine projects. Appropriate studies to evaluate impacts to critical wetland or riparian vegetation, aquatic primary producers, benthic macroinvertebrates, or wildlife may be warranted for a very limited number of projects.

Required Instream Flows for Protection of the Chesapeake Bay

Minor changes in the freshwater input to estuaries can have far-reaching effects on estuarine biota. Many estuarine species have salinity requirements that may vary with the stage of their life cycle (Hagan and Roberts, 1973).

The Susquehanna River provides 50 percent of the total freshwater input to the Chesapeake Bay. Although agreement has not been reached concerning the required freshwater flows needed to sustain the integrity of the Chesapeake Bay, the Chesapeake Bay Study prepared by the U.S. Army Corps of Engineers (1984) stated that decreases in the freshwater input to the bay have had serious environmental, social, and economic impacts in the past and are expected to have more significant effects in the future.

The SRBC low flow management framework planning reports (Heicher et al., 1987; Heicher and Hirschel, 1988, 1989, 1990, 1991a, and 1991b) have repeatedly stressed that the bay's inflow needs must be identified if definitive low flow goals are to be established.

Although much work has been done to improve the water quality of the bay, the freshwater inputs that are also critical to the bay's biological integrity have been largely ignored. The time has come to also address this important issue.

GLOSSARY

allochthonous - originating outside of the stream. Allochthonous plant materials such as leaves can fall into the stream and serve as a source of nutrients for some aquatic life.

autochthonous - originating in the stream

autotrophic - able to produce organic nutrients from inorganic raw materials

benthic - bottom-dwelling

estuary - an inlet, embayment, or river mouth under tidal influence

fluvial - associated with a river or rivers

food web - description of the interaction of organisms dependent on each other for food, through which energy and materials may move

habitat - native environment; place where an organism normally lives or grows

heterotrophic - not able to produce organic nutrients from inorganic raw materials; requiring organic nutrients from outside sources

hyporheic zone - area beneath the surface of the stream bed that contains unconsolidated material such as gravel, sand, silt, etc. and is generally suitable for colonization by aquatic invertebrates

invertebrate - animal that lacks a backbone or spinal column

invertebrate drift - phenomenon by which invertebrates detach from the stream substrate and drift downstream for a period of time

lentic - associated with standing water such a pond or lake

lotic - associated with running water such as a stream or river

macrophytes - plants that can readily be seen with the naked eye

macroinvertebrates - invertebrates that can readily be seen with the naked eye

obligate wetland plants - plants that under natural conditions nearly always occur in wetlands periphyton - microscopic plants growing on stream substrate; attached algae

primary production - formation of energy (or material) by green plants

riparian - associated with or living along the bank of a river or other body of fresh water

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